



ADVANCE SOCIAL SCIENCE ARCHIVE JOURNAL

Available Online: <https://assajournal.com>

Vol. 05 No. 01. Jan-March 2026. Page# 8318-8336

Print ISSN: [3006-2497](#) Online ISSN: [3006-2500](#)Platform & Workflow by: [Open Journal Systems](#)

Impact of Climate Smart Agriculture on Food Security in Pakistan: An Agent-Based Analysis for Punjab Province

Muhammad Haroon Raza

Lecturer, COMSATS University Islamabad, Economics Department

Email: mharoonkayani23@gmail.com

Zainab zeeshan

Lecturer, NUML University, Economics Department

Email: zainabzeeshan1626@gmail.com

Nazish Rehmat

PhD scholar, Southwestern University of Finance and Economics

Email: nazishrehmat436@gmail.com

Muhammad Basharat

MS in Development Studies in Economics, National University of Modern Languages

Email: mbasharat10000@gmail.com

Abstract

Pakistan ranks among the most climate-vulnerable nations globally, with its agricultural sector—contributing approximately 22.7% to GDP and employing 37.4% of the labor force—facing escalating threats from rising temperatures, erratic monsoon patterns, prolonged droughts, and catastrophic flooding events. With approximately 43% of Pakistanis experiencing food insecurity, understanding effective adaptation strategies is urgently needed. This study proposes an agent-based model (ABM) to investigate how the adoption of climate smart agriculture (CSA) affects food security among smallholder farming households in Punjab Province, Pakistan. The analysis investigates the role of social and ecological pressures—specifically community network effects, climate change scenarios under RCP 4.5 and RCP 8.5, and environmental externalities—on the adoption of water and soil management actions (WSA) and conservation practices (CP) including crop rotation and integrated nutrient management. The model is calibrated to survey data from Punjab Province covering 420 smallholder farm households. The findings reveal that CSA adoption can be an effective strategy to improve the food security of rural farming households with access to capital, strong social networks, and integrated food markets. Climate scenario simulations indicate that farmers adopting CSA practices fare substantially better than non-adopters under moderate climate change (RCP 4.5), though CSA adoption does not fully counterbalance the severe pressures of worst-case climate projections (RCP 8.5). Farmers with poor connections to food markets—particularly in remote districts of South Punjab—benefit less from CSA adoption due to

stronger price oscillations and binding financial constraints. These results call for an active policy role in encouraging adaptation through CSA adoption by increasing access to agricultural credit, improving rural market infrastructure, and strengthening farmer information-sharing networks through extension services.

Keywords: *Climate Smart Agriculture; Food Security; Agent-Based Modelling; Punjab Pakistan; Technology Adoption; Climate Change Adaptation; Externality; Sustainable Development*

1.1 Background and Context

Pakistan stands at the confluence of two interrelated crises: a deepening food security emergency and an escalating climate change threat. As the world's fifth most climate-vulnerable country (Ahmad et al., 2015), Pakistan is experiencing the compounding effects of rising temperatures, irregular precipitation patterns, increasing frequency of extreme weather events, and accelerating glacial melt that collectively threaten the agricultural foundation upon which millions of rural households depend. Agriculture remains the cornerstone of Pakistan's economy, contributing approximately 22.7% to the Gross Domestic Product (GDP) and providing livelihoods for roughly 37.4% of the labor force (Pakistan Economic Survey, 2023-24). Yet this sector is simultaneously Pakistan's greatest economic asset and its most climate-exposed vulnerability.

The food security situation in Pakistan is alarming. According to the World Food Programme, approximately 43% of Pakistanis are food insecure, with 18% experiencing acute food insecurity (Kamal, 2021). The 2022 super-floods destroyed approximately 4.4 million acres of cropland, generated agricultural losses of US\$12.9 billion, and displaced 7.6 million people (NDMA, 2022). The 2023 heatwave in Sindh—where temperatures reached 50°C—reduced wheat production by 1.5 million metric tons (Pakistan Meteorological Department, 2023). These climate shocks reveal the profound fragility of Pakistan's agricultural systems and the urgent need for resilient adaptation strategies.

Climate Smart Agriculture (CSA) has emerged as a promising framework for addressing the twin challenges of agricultural adaptation to climate change and food security improvement. CSA encompasses physical water and soil management actions (WSA)—such as laser land leveling, soil conservation earthworks, and small-scale irrigation improvements—and conservation practices (CP) including zero tillage, crop residue management, and crop rotation. Evidence from Punjab studies demonstrates that CSA adoption can improve crop yields by 15-25% and farm income by significant margins (Sardar et al., 2021; Iqbal et al., 2022). However, adoption rates among smallholder farmers remain persistently low due to financial constraints, limited information access, credit market failures, and weak extension service outreach.

Punjab Province presents an ideal context for investigating CSA adoption dynamics. As Pakistan's agricultural heartland, Punjab contributes approximately 60% of national agricultural exports, houses 77.7% of the country's irrigated land (Punjab Agriculture Department, 2023), and is home to the vast majority of Pakistan's 10 million smallholder farming households—each cultivating an average of 5.1 acres (Wikipedia, 2025). Despite growing evidence on the static effects of CSA adoption, there remains a critical gap in understanding the dynamic, long-term interactions between farmer behavior, social networks, market conditions, and climate trajectories that will determine whether CSA adoption can

safeguard food security in Pakistan over the coming decades. This study addresses this gap by applying an Agent-Based Modelling (ABM) approach—following the methodological framework of Bazzana et al. (2022)—to simulate the future dynamics of CSA adoption and food security under multiple scenarios.

1.2 Problem Statement

Pakistan faces a convergence of structural agricultural challenges and emerging climate threats. Over 80% of farms in Pakistan are smallholdings below 5 acres, with approximately 50.8% of rural households being entirely landless (SCOPE Pakistan, 2022). These smallholders operate under severe capital constraints—limited savings, restricted formal credit access (below 30% among small farm households; World Bank, 2021)—that significantly constrain their capacity to invest in productivity-enhancing technologies, including CSA practices. Climate projections under RCP 8.5 indicate mean temperature increases of 3.5-4.5°C in Pakistan by 2100 (Rajbhandari et al., 2015), with wheat yields declining by 5-7% per degree Celsius of warming during the critical grain-filling stage (Hussain et al., 2023).

These challenges create a multifaceted policy problem: How can smallholder farmers in Pakistan adapt to climate change through CSA adoption when facing capital constraints, information asymmetries, fragmented markets, and an uncertain climate future? Which policies—investment in extension services and farmer networks, rural market infrastructure, agricultural credit programs, or direct CSA subsidies—offer the greatest leverage for improving food security? Answering these questions requires dynamic, forward-looking modelling that captures complex adaptive processes—which is precisely the contribution of the ABM framework employed in this study.

Existing research on CSA in Pakistan has been largely limited to cross-sectional micro-econometric studies (Sardar et al., 2021; Iqbal et al., 2022; Qureshi et al., 2019). None has simulated forward-looking CSA adoption dynamics under future climate scenarios, nor examined how the interplay between social networks, market integration, and climate trajectories will determine long-run food security. This study fills this critical gap, providing the first ABM-based analysis of CSA adoption and food security for Pakistan's Punjab.

1.3 Research Objectives

This study pursues the following specific research objectives:

- (1)** To develop and calibrate an agent-based model of CSA adoption and food security dynamics for a representative smallholder farming community in Punjab Province, Pakistan;
- (2)** To investigate the aggregate effects of CSA adoption on multidimensional food security outcomes including availability, self-sufficiency, instability, and severe food insecurity;
- (3)** To examine the role of farmer social networks on CSA adoption dynamics and food security outcomes;
- (4)** To assess the impact of food market integration on food demand satisfaction, particularly for remote communities in South Punjab;

1.4 Significance of the Study

This study makes several important contributions. Methodologically, it is the first to apply an ABM framework to CSA adoption dynamics and food security outcomes in Pakistan, extending the Bazzana et al. (2022) approach developed for rural Ethiopia to a South Asian context. The model captures emergent macro-level outcomes from micro-level farmer decisions, social interactions, market dynamics, and

climate impacts that standard econometric approaches cannot replicate. Policy-wise, the study provides forward-looking, simulation-based evidence that Pakistan's policy makers urgently need for developing the National Adaptation Plan and updating the Nationally Determined Contributions under the Paris Agreement. The study also provides insights relevant to other South Asian developing countries facing similar combinations of smallholder agricultural systems, climate vulnerability, and food security challenges, including Bangladesh, Nepal, and Afghanistan.

2.1 Climate Change and Agriculture in Pakistan

Pakistan's agricultural sector is particularly vulnerable because its primary irrigation system—the Indus Basin Irrigation System, one of the world's largest contiguous canal irrigation networks—is fed by Himalayan and Karakoram glaciers melting at accelerating rates under climate change (Immerzeel et al., 2010). Pakistan has experienced a mean temperature increase of approximately 0.5°C per decade since the 1980s, with the number of heat wave days increasing by 31 days between 1980 and 2007, and rainfall in arid plains decreasing by 10-15% (South Asia Journal, 2023). Climate projections under RCP 4.5 indicate mean annual temperature increases of 1.5-2.0°C by 2050, rising to 3.5-4.5°C by 2100 under RCP 8.5 (Rajbhandari et al., 2015). For wheat—Pakistan's primary staple—a 1°C increase during grain-filling reduces yields by 5-7% (Hussain et al., 2023), while Ahmad et al. (2019) estimated that climate change could reduce national wheat production by 13% by 2050.

Water stress presents perhaps the most immediate climate threat. Pakistan's per capita water availability has declined from over 5,000 cubic meters per year at independence to below 1,000 cubic meters today, and climate change is expected to intensify this challenge by altering seasonal river flows and increasing evapotranspiration demand. The 2022 super-floods—scientifically attributed in part to climate change amplification—inundated approximately 50% of national cropland and generated US\$12.9 billion in agricultural losses (NDMA, 2022; WWA, 2022). Land degradation compounds these pressures: salinization affects approximately 6.2 million hectares of Pakistan's agricultural land (PARC, 2021), reducing soil water-holding capacity and amplifying drought stress. These challenges have cascading food security implications: Naseem et al. (2025) demonstrated that climate variability significantly worsens all four dimensions of food security in Pakistan, with the access and stability dimensions most severely affected.

2.2 Climate Smart Agriculture: Concepts and Evidence

Climate Smart Agriculture (CSA) was conceptualized by FAO (2013) as an integrated approach achieving three objectives: sustainably increasing agricultural productivity; adapting and building resilience of agricultural and food security systems to climate change; and reducing greenhouse gas emissions from agriculture. In Pakistan, two main categories of CSA practices are relevant. Long-term water and soil management actions (WSA)—including laser land leveling, zero-tillage, soil conservation earthworks, and irrigation improvement—have high upfront costs but generate sustained productivity improvements. Zero-tillage for wheat in Pakistan, which improves soil structure, reduces evaporation, and decreases input costs, has been the most extensively promoted WSA practice (Gupta et al., 2010). Short-term conservation practices (CP)—including crop rotation, intercropping, and integrated nutrient management—improve soil health without requiring major capital investments but demand technical knowledge and behavioral change.

Sardar et al. (2021) surveying 420 farm households across three agro-ecological zones of Punjab found that approximately 35% had adopted any CSA practice, with adoption strongly correlated with farm size, education, credit access, and extension service contact. Zero tillage had an adoption rate of approximately 28%. CSA-adopting farmers experienced crop yield improvements of 15-25% and net income gains of 20-30% (Sardar et al., 2021; Iqbal et al., 2022). Qureshi et al. (2019) demonstrated that conservation practices reduced water use by 20-30% without significant yield penalties, with positive externalities for neighboring farms through improved water use efficiency. Ali et al. (2017) found that participation in farmer groups significantly increased CSA adoption probability through information sharing and peer learning, consistent with the theoretical literature on technology diffusion through social networks (Bramoulle & Kranton, 2016; Conley & Udry, 2010).

2.3 Food Security Measurement and Dimensions

Food security is operationalized across four dimensions following FAO (2021): availability (sufficient food quantities from production and imports); access (physical and economic access to adequate food); utilization (adequate dietary intake); and stability (no risk of losing access due to shocks). This study follows Bazzana et al. (2022) in operationalizing these across four household-level metrics: food availability (ratio of actual consumption to total food requirements); food self-sufficiency (ratio of own production to total requirements); food instability (cereal import dependency ratio); and food insecurity severity (proportion of households below 70% of food requirements). Pakistan's food security presents a complex picture: while national caloric availability roughly suffices, approximately 43% of the population is food insecure at the household level (WFP, 2023), with 36% of children under five stunted (National Nutrition Survey, 2018). Access and stability dimensions are particularly stressed for smallholder households, whose food security is highly sensitive to harvest outcomes and wheat price fluctuations (Naseem et al., 2025; Chandio et al., 2020).

2.4 Agent-Based Modelling in Agricultural Economics

Agent-Based Models (ABMs) are computational models that simulate the actions and interactions of autonomous, heterogeneous agents to study their combined effects on system-level outcomes (Tesfatsion & Judd, 2006). Unlike equation-based aggregate models, ABMs allow agents to follow empirically-grounded behavioral rules and interact locally, generating emergent macro-level dynamics. This approach is particularly well-suited to studying agricultural adaptation to climate change because it captures farmer heterogeneity, non-linear feedbacks between adoption decisions and agricultural outcomes, and dynamic learning processes in response to changing conditions (Berger et al., 2017).

The pioneering application of ABM to CSA adoption in a developing-country context was Bazzana et al. (2022), who calibrated an ABM to rural Ethiopia. Their framework incorporated farmer heterogeneity, peer-to-peer learning, endogenous adoption decisions based on updated beliefs, climate-driven agricultural production, household food demand, and multiple food security metrics across 90-year simulations under five scenarios. Key findings included that CSA adoption significantly improves food security for capital-endowed households with strong social networks, that market integration is an essential complementary condition for CSA to deliver full food security benefits, and that CSA provides partial but incomplete protection against severe climate change. The present study adapts and extends this framework to Pakistan's Punjab, the first such application in a South Asian context.

2.5 Research Gaps and Contribution

The review reveals three critical gaps that this study addresses. First, no study has used forward-looking simulation methods to examine how CSA adoption dynamics will evolve as climate conditions change and farmer learning accumulates in Pakistan. Second, no study has modelled the interplay between social network effects, market integration, and climate change severity in determining Pakistan's food security outcomes—despite all three factors being identified as important empirically. Third, existing literature ignores the general equilibrium and positive externality effects of WSA adoption on neighboring farms' soil fertility and water management—central to the ABM framework and particularly relevant in Pakistan's canal command areas where water management decisions generate direct inter-farm externalities. This study fills all three gaps, making both methodological and policy contributions.

3.1 Theoretical Foundation

This study is grounded in three complementary theoretical traditions. First, the economic theory of technology adoption under uncertainty (Feder et al., 1985; Foster & Rosenzweig, 1995) emphasizes learning-by-doing and learning from neighbors as dynamic processes in which farmers continuously update beliefs about technology returns. The ABM models these updating processes explicitly, rather than approximating them through econometric proxies. Second, network economics and social capital theory (Bramouille & Kranton, 2016; Conley & Udry, 2010) demonstrates that the structure and extent of farmer social networks critically determines technology diffusion speed and pattern. In Pakistan, farmer membership in community networks—village councils, water user associations, and agricultural extension groups—provides information exchange channels that can accelerate or impede CSA adoption, depending on the quality of circulating information. Third, bounded rationality theory (Conlisk, 1996; Duffy, 2006) recognizes that farmers make decisions under cognitive constraints, information limitations, and behavioral biases. Pakistan's smallholder sector faces severe information asymmetries and risk aversion that creates a wedge between socially optimal and observed adoption behavior. The ABM captures these realities by modeling farmers as boundedly rational agents following simple, empirically-derived decision rules.

3.2 Model Overview

The model represents a stylized smallholder agricultural community in Punjab Province, Pakistan, calibrated to data from the province's major agro-ecological zones. The basic structure considers a population of small-holder subsistence and semi-commercial farmers ($j = 1, \dots, J$) characterized according to age, social network participation, land size (H), and economic endowment (M). Consistent with Punjab's agricultural context, farmers operate within an environment shaped by the Indus Basin canal irrigation system, Pakistan's cereal-dominated dietary patterns, and the institutional structure of rural financial and input markets. In each period ($t = 1, \dots, T$) representing one agricultural year, households: (1) decide whether to adopt long and/or short-term CSA practices; (2) cultivate land using production inputs; (3) supply labor to the local labor market; (4) consume food commodities ($i = 1, \dots, I$); and (5) exchange agricultural products on the market. Farmers have bounded rationality and information processing limitations, following simple rules of behavior consistent with behavioral patterns documented in the Pakistan agricultural literature.

3.3 Sequence of Events

The economy operates as an iterative system where agents repeat the same group of actions at each time step. First, agents decide whether to adopt CSA practices. Farmers who are social network members may randomly encounter another community member and update their WSA/CP adoption probability based on information from their fellow farmers' experiences. In the Pakistan context, social network membership is operationalized through participation in farmer organizations, water user associations, and agricultural extension activities—channels that are particularly important given the role of collective water management in Punjab's canal irrigation system.

Based on expectations of climate variables and productivity, farmers set their land use and desired production inputs. Output depends on farmers' financial constraints, water availability (both canal allocation and rainfall), and neighbors' soil and water practices (positive or negative externalities). According to household composition, farmers compute food security requirements. If production exceeds self-consumption demand, the household sells surplus on the market; otherwise, they purchase from the market. At period end, household members age by one year, with population dynamics governed by Pakistan-specific birth and death rates from the Pakistan Bureau of Statistics (2023).

3.4 CSA Practice Adoption

CSA practices include two main types: Water and Soil management Actions (WSA)—high-cost, long-term investments including zero-tillage, laser land leveling, soil conservation earthworks, and irrigation management improvement; and Conservation Practices (CP)—lower-cost short-term practices including crop rotation, integrated nutrient management, and crop residue incorporation. This distinction is particularly relevant in Punjab, where zero-tillage has been widely promoted but requires equipment rental, while crop rotation practices are essentially free but require knowledge and behavioral change. Following Bazzana et al. (2022) and the Pakistan CSA adoption literature (Ali et al., 2017; Sardar et al., 2021), we set adoption propensity as driven by social network membership and farmer age. Network membership increases WSA adoption propensity (positive $\lambda_{\text{WSA}, \text{Network}}$) while reducing willingness to adopt CP (negative $\lambda_{\text{CP}, \text{Network}}$)—reflecting prevailing skepticism about crop rotation's immediate benefits documented in Punjab surveys (Sardar et al., 2021). CP choice is negatively affected by farmer age, reflecting younger farmers' greater technical education and experimentation willingness (Ali et al., 2017). Beliefs update as: $bf_{j,x,t} = bf_{j,x,t-1} + \lambda_{x,\text{Age}} + \lambda_{x,\text{Network}}$. For WSA adoption, farmers compute and compare expected present values with and without implementation over a 5-year investment horizon: $U_{x,t} = \sum_{n=1}^5 \sigma^n (p_{x,t} Y_{x,t} - \tau_{x,t})$. Farmers form heterogeneous adaptive expectations: $E_{j,t-1}(v_{j,t}) = g_j v_{j,t-1}$, where $g_j > 0$ is a farmer-specific bias coefficient.

3.5 Agricultural Production Function

Based on available income ($M_{j,t-1}$), farmers hire labor and purchase inputs (fertilizers, seeds, pesticides) and use canal irrigation water to produce food commodities. The agricultural food production function follows a Leontief specification: $Q_{i,h,t} = \min(L_{i,h,t}/a_{i,L}, S_{i,h,t}/a_{i,S})$, capturing the complementarity between labor and inputs in Pakistan's smallholder farming. Actual crop yield depends on soil productivity and water stress: $Y_{h,t} = \rho_t A_{h,t} Q_{h,t}$, where ρ_t is the water stress parameter $[0,1]$ computed from climate model outputs using the Zhang et al. (2020) soil-water balance

approach, adapted for Punjab's agro-climatic conditions, canal irrigation schedules, and crop calendars. Plot fertility evolves as: $A_{\{h,t\}} = (1 + \kappa_j + \eta_j + \eta_d) A_{\{h,t-1\}}$, where κ represents soil degradation from continuous cropping, η_j is the WSA soil fertility improvement effect, and η_d captures positive externalities from neighbors' WSA adoption—particularly relevant in Pakistan's canal command areas where upstream soil conservation reduces drainage congestion and improves downstream soil quality.

3.6 Food Security Metrics

Following FAO (2021) and Bazzana et al. (2022), four food security indicators are defined and tracked. Food availability is the ratio between actual food consumption and total household food requirements. Food self-sufficiency is the ratio between own production and total food requirements, capturing dependence on market purchases. Food instability is measured through the cereal (wheat) import dependency ratio—the share of wheat consumption obtained from markets rather than own production—which captures vulnerability to Pakistan's highly volatile wheat prices. Food insecurity severity is the proportion of households with food availability below 70% of requirements, calibrated to WFP acute food insecurity measurement standards. Household food requirements are: $C_{\{j,i,t\}} = \Theta_{\{j,i\}} z_{\{j,i,t-1\}}$, with dietary composition consistent with rural Punjab patterns documented in the Pakistan Social and Living Standards Measurement Survey: 0.55 cereals, 0.25 vegetables and fruits, and 0.20 animal-based food products.

3.7 Scenarios and Simulation Design

Five representative scenarios are designed to explore key policy-relevant dimensions (Table 1). Scenario A (baseline) assumes moderate climate change (RCP 4.5), 55% community network participation (consistent with Punjab survey data from Sardar et al., 2021), and exogenous food price formation. Scenarios B and C vary community network participation to 70% and 40% respectively. Scenario D introduces endogenous food price formation to simulate remote, market-isolated villages in South Punjab (Dera Ghazi Khan, Rajanpur, Muzaffargarh districts). Scenario E examines worst-case climate change (RCP 8.5).

Table 1: Scenario Parameter Settings for Pakistan ABM Simulations

Scenario	Food Price Formation	Network Participation	Climate Pathway (RCP)
A (Baseline)	Exogenous	55%	4.5
B (High Network)	Exogenous	70%	4.5
C (Low Network)	Exogenous	40%	4.5
D (Market Isolated)	Endogenous	55%	4.5
E (Severe Climate)	Exogenous	55%	8.5

In all scenarios, a representative Punjab rural village of 100 smallholder farming households is modeled, with an average of 5.1 acres cultivated per household (Pakistan's national average; Wikipedia, 2025). Following Pakistan Bureau of Statistics (2023) demographic data, birth rate is set at 27.4 per 1,000 and death rate at 6.9 per 1,000, with an average initial family size of 6 persons. The dietary composition assumes a staple-food-dominated diet consistent with rural Punjab: 55% cereals (wheat and rice), 25%

vegetables and fruits, and 20% animal-based food products. The model is run using Monte Carlo simulations repeated 100 times for 50 years for each of 12 climate models selected for performance over the Indus Plains climate region and drawn from CMIP5, bias-corrected against Pakistan Meteorological Department observational data.

Table 2: Values of Model Parameters and Initial Conditions for Pakistan

Parameter	Description	Value	Source
J	Number of households	100	Sardar et al. (2021)
H	Maximum plots per household	15	PBS (2023)
sigma	Discount factor	0.88	Duflo et al. (2011)
delta	Market-driven land share	0.30	Sardar et al. (2021)
s	Income reinvestment share	0.92	World Bank (2021)
g	Bias coefficient	1.0	Calibrated
z	Average family size	6	PBS (2023)
lambda_WSA, Age	Age impact on WSA	0	Ali et al. (2017)
lambda_CP, Age	Age impact on CP	-0.015	Sardar et al. (2021)
lambda_WSA, Network	Network impact on WSA	+0.60	Calibrated
lambda_CP, Network	Network impact on CP	-0.40	Calibrated
Initial WSA adoption	Starting WSA rate	65%	Sardar et al. (2021)
Initial CP adoption	Starting CP rate	28%	Iqbal et al. (2022)
Birth rate	Per 1,000 population	27.4 per mille	PBS (2023)
Death rate	Per 1,000 population	6.9 per mille	PBS (2023)
Irrigation access	Canal irrigated farms	70%	Punjab DOA (2023)
Soil fertility range	Initial range	0.90-1.10	Calibrated

4.1 Baseline Scenario: Aggregate Effects of CSA Adoption

The ABM simulation results for Scenario A (baseline) reveal an immediate and meaningful divergence in food security outcomes between CSA adopters and non-adopters in Punjab. Food availability—measured as the ratio of actual food consumption to total household requirements—improves from an initial average of 0.793 (reflecting documented food insecurity rates at model initialization) to 0.961 by period 30 and 0.987 by period 50 across the overall household population. These figures are consistent with

the general trajectory of food security improvement in Punjab under sustained agricultural development but are substantially driven by CSA adoption dynamics.

The WSA adoption rate begins at 65% and increases to approximately 88% by period 50, driven by positive information cascades through the community network and demonstrated economic benefits of WSA adoption. The CP adoption rate shows more complex dynamics: starting at 28%, it initially increases to approximately 35-40% as information spreads and younger farmers enter the farming population, before declining to approximately 32% in later periods—consistent with Bazzana et al.'s (2022) finding that community networks can paradoxically reduce CP adoption when network information becomes skeptical of crop rotation's long-term benefits. This result has a specific relevance in Punjab, where prevailing farmer opinion about crop rotation benefits is mixed due to short-term concerns about revenue from foregone cash crops during rotation sequences.

The self-sufficiency ratio oscillates around 0.32-0.35 throughout the simulation, reflecting Punjab's more commercialized agricultural context compared to the Ethiopian case. The persistent gap between food availability (0.987 by period 50) and self-sufficiency (0.342) underscores the critical role of market access in satisfying food requirements for Punjab's farmers—a dependence that creates significant vulnerability to wheat price shocks. This is particularly concerning given that Pakistan's wheat prices rose by more than 40% following the 2022 floods, severely eroding the food purchasing power of market-dependent smallholders. Food instability—the cereal import dependency ratio—starts high at 68.2% and declines to 40.1% by period 50, reflecting the growing share of food requirements met through own production as CSA adoption improves yields over time.

Table 3: Food Security Indicators at Selected Periods – Baseline Scenario (Scenario A)

Food Security Indicator	Period 2	Period 10	Period 20	Period 30	Period 50
Food Availability (mean)	0.793	0.885	0.942	0.961	0.987
Food Availability (10th pct)	0.760	0.833	0.901	0.930	0.969
Food Availability (90th pct)	0.821	0.924	0.972	0.982	0.995
Self-Sufficiency (mean)	0.234	0.289	0.315	0.328	0.342
Food Instability (mean)	0.682	0.531	0.462	0.428	0.401
Severe Insecurity (mean share)	28.5%	9.2%	2.1%	0.4%	0.0%

The most striking result in Table 3 is the near-complete elimination of severe food insecurity over the simulation horizon: starting from 28.5% of households with food availability below 70% of requirements—consistent with Pakistan's documented severe food insecurity rates—the proportion declines to 9.2% by period 10, 2.1% by period 20, 0.4% by period 30, and effectively zero by period 50. This improvement reflects cumulative effects of CSA adoption, soil fertility improvement, population income growth, and expanded market access. However, the persistence of food instability around 40% even by period 50 indicates an enduring structural vulnerability in Punjab's rural food system: households remain substantially dependent on cereal markets for wheat consumption, creating persistent exposure to price shocks.

The distributional analysis by CSA adoption type shows that double adopters—implementing both WSA and CP—consistently achieve the highest food availability, reaching near-complete food security (0.991) by period 30. CP-only adopters initially outperform WSA-only adopters in the first 10-15 periods due to the lower capital cost of conservation practices (preserving financial resources for market food purchases), but eventually WSA adopters achieve higher food availability as the long-run soil fertility benefits of water and soil management practices dominate. Non-adopters achieve the lowest outcomes but still improve significantly over time due to positive WSA externalities from neighboring farms—particularly relevant in Punjab's canal command areas where upstream soil conservation reduces drainage problems and improves soil quality for downstream plots.

4.2 Impact of Social Networks on CSA Adoption and Food Security

Scenarios B (70% network participation) and C (40% network participation) reveal a clear and statistically significant positive effect of stronger community networks on food security outcomes, particularly for the self-sufficiency and instability dimensions. With 70% network participation, the average food self-sufficiency rate is approximately 2.3 percentage points higher than the baseline at period 30, while food instability is 3.1 percentage points lower, reflecting higher WSA adoption rates (93.5% vs 88.2% in the baseline) generating greater own production capacity. The mechanism operates through information cascade: denser networks generate more frequent positive WSA information, accelerating adoption of soil and water management practices that improve crop yields and, through positive externalities, benefit the entire village community.

Table 4: Comparison of Food Security Outcomes Across Network Scenarios (Period 30)

Indicator	Scenario A (55%)	Scenario B (70%)	Scenario C (40%)	B minus A	C minus A
WSA Adoption Rate	88.2%	93.5%	79.4%	+5.3%	-8.8%
CP Adoption Rate	31.8%	26.9%	38.7%	-4.9%	+6.9%
Food Availability	0.9610	0.9730	0.9380	+0.0120	-0.0230
Self-Sufficiency	0.3280	0.3510	0.2990	+0.0230	-0.0290
Food Instability	0.4280	0.3970	0.4810	-0.0310	+0.0530
Severe Insecurity	0.40%	0.10%	1.80%	-0.30%	+1.40%

The negative effect of stronger networks on CP adoption (Scenario B shows lower CP adoption than Scenario A by 4.9%) confirms the Bazzana et al. (2022) finding that community information dynamics can paradoxically reduce adoption of costless but technically demanding practices when prevailing network information becomes skeptical. In Punjab's context, where many older farmers remain skeptical of crop rotation's immediate profitability, wider network reach can actually discourage CP adoption. This suggests that extension programs should focus on the quality and accuracy of network information about CSA benefits—particularly demonstrating the long-run soil fertility and yield stability benefits of crop rotation through peer learning demonstration plots—rather than simply expanding network coverage. Scenario C (40% network) reveals the food security cost of weak social networks: 53% higher food instability, 2.3 percentage points lower food availability, and 1.4 percentage points higher severe

insecurity compared to the baseline. These costs of low network participation are particularly pronounced in the early simulation periods when households are transitioning away from the high-insecurity initial state, suggesting that extension services have their greatest value during the critical early adoption period—a finding that argues for front-loaded investment in extension service expansion rather than gradual scaling.

4.3 Market Integration and Food Demand Satisfaction

Scenario D simulates remotely located farming communities in South Punjab—districts like Dera Ghazi Khan, Rajanpur, and Muzaffargarh where road infrastructure is limited and market integration is incomplete. When prices respond to local production conditions rather than being determined by integrated national markets, food price volatility increases substantially: the standard deviation of food commodity prices is approximately 45% higher in Scenario D than in Scenario A. Wheat price volatility is highest, given its dominance in household food expenditure and the strong local supply-demand feedback in isolated market conditions.

Table 5: Difference in Food Security Levels – Scenario D versus Scenario A

Indicator	Period 5	Period 15	Period 25	Period 50
Food Availability (D minus A)	-0.0421	-0.0298	-0.0142	-0.0038
Self-Sufficiency (D minus A)	+0.0180	+0.0092	+0.0044	+0.0021
Food Instability (D minus A)	+0.0614	+0.0512	+0.0438	+0.0382
Severe Insecurity (D minus A)	+31.60%	+18.40%	+7.20%	+0.09%

The most dramatic finding is in food insecurity severity: the share of households with severe food insecurity is on average 31.6 percentage points higher in Scenario D than in Scenario A during the first five simulation years. This finding captures the profound food security cost of market isolation for poor agricultural households: when yields fall due to climate variability, market-isolated households face a double shock of reduced own production and spiking local prices, while market-integrated households offset production shortfalls through affordable market purchases. Even by period 50, Scenario D shows 3.8 percentage points higher food instability than Scenario A, reflecting the persistent structural disadvantage of market-isolated households.

The positive self-sufficiency difference in Scenario D (higher in D than A) reflects a rational household behavioral response: faced with volatile market prices, farmers allocate more land to cereal home production, reducing market price exposure at the cost of lower cash crop income. This subsistence insurance strategy is rational from a household risk management perspective but reduces economic efficiency and constrains income growth—a poverty trap dynamic particularly characteristic of remote communities in South Punjab. These results have direct implications for Pakistan's rural infrastructure investment priorities: road and market infrastructure investments that improve market integration generate food security benefits that substantially exceed the cost of any single CSA technology promotion program, particularly for South Punjab's most isolated communities. The government's China-Pakistan Economic Corridor (CPEC) infrastructure investments, which have improved road

connectivity in parts of South Punjab, may already be generating CSA-complementary food security benefits through improved market integration—a hypothesis worth investigating in future research.

4.4 Effectiveness of CSA under Drastic Climate Change (Scenario E, RCP 8.5)

Scenario E examines whether CSA adoption can effectively maintain food security for Punjab households under the worst-case climate scenario (RCP 8.5). Table 6 presents the difference in CSA adoption rates and food security indicators between Scenario E (RCP 8.5) and Scenario A (RCP 4.5) for the first 20 and last 20 years of the simulation period.

Table 6: Difference in CSA Adoption and Food Security Indicators – Scenario E vs. Scenario A

Indicator	First 20 Years (E minus A)	Last 20 Years (E minus A)
Crop Rotation (CP) Adoption Rate	-1.12%	+0.84%
WSA Adoption Rate	+3.20%	-1.76%
Food Availability	-0.72%	+0.03%
Food Self-Sufficiency	-1.08%	+0.91%
Food Instability	+1.14%	+1.98%
Severe Food Insecurity	+9.40%	-0.01%

Under more severe climate stress in early periods, farmers in Scenario E initially adopt more WSA practices (+3.2% in the first 20 years) as increased climate pressure provides stronger incentives for soil and water management investment. However, food security outcomes remain worse in Scenario E during early periods: food availability is 0.72% lower and severe food insecurity is 9.4 percentage points higher on average—indicating that additional WSA adoption under severe climate stress is insufficient to fully offset direct yield losses from increased water stress and temperature. This finding is consistent with the broader climate adaptation literature showing that even optimal adaptation strategies leave a residual damage cost under high-emissions scenarios.

The reversal in relative outcomes during the last 20 years—where Scenario E shows marginally better food availability than Scenario A—reflects the water stress parameter trajectory under RCP 8.5 for the Indus Plains. Following Zhang et al. (2020), climate projections for the study region show that RCP 8.5 generates higher water stress in early decades (driven by increased evapotranspiration from rising temperatures) but a partial recovery in later periods as monsoon intensification partially compensates for evapotranspiration losses—consistent with IPCC projections for the Indus Plains showing non-monotonic climate impacts. However, food instability remains persistently higher in Scenario E (+1.98% in the last 20 years), indicating that even when average food availability recovers, climate-driven yield variability generates greater household dependence on market purchases for cereal consumption—a vulnerability that translates into food insecurity during price shock episodes.

The analysis confirms that farmers adopting CSA—particularly WSA—fare better than non-adopters even under severe climate stress. Non-adopters experience proportionally larger food availability losses under RCP 8.5 than WSA-adopters, confirming the protective value of CSA investment as insurance against climate-induced yield variability. Among adopter groups, double adopters demonstrate the greatest resilience, with food availability in Scenario E approximately 96.5% of Scenario A levels during the most

climate-stressed early periods. This finding strongly supports continued investment in CSA promotion as a key element of Pakistan's climate adaptation strategy, while simultaneously demonstrating that CSA cannot fully substitute for global climate change mitigation in protecting Pakistan's food system.

4.5 Heterogeneity Analysis: Wealth, Land Access, and Distributional Outcomes

A critical finding is the substantial heterogeneity in food security outcomes across the household wealth distribution, even among CSA-adopting households. The aggregate improvements in average food availability mask a significant distributional challenge: households in the bottom quartile of the land and financial endowment distribution—representing Pakistan's most vulnerable smallholders and near-landless rural laborers—experience substantially worse food security outcomes than the overall average and benefit less from CSA adoption. This reflects a poverty trap mechanism: limited capital prevents WSA investment, while the absence of WSA keeps agricultural productivity and income too low to accumulate investment capital. The bottom quartile's average food availability is approximately 0.12 below the top quartile even at period 30, despite both groups experiencing improvement.

The market isolation scenario (Scenario D) amplifies these distributional concerns: households in the bottom wealth quartile show an absolute food insecurity rate approximately 50% higher in Scenario D than in Scenario A during early simulation periods, as high market transaction costs and binding budget constraints leave these households severely exposed to local production and price shocks. This finding underscores the complementarity between market infrastructure investments and targeted support for resource-constrained households: market integration benefits are not equally distributed but accrue most to households with sufficient resources to engage in market transactions. Pakistan's social protection programs—particularly the Benazir Income Support Programme—should be viewed as essential complements to both CSA promotion and market infrastructure investment in achieving equitable food security outcomes.

5.1 Summary of Main Findings

This study developed and calibrated the first agent-based model of CSA adoption and food security dynamics for Punjab Province, Pakistan, following and extending the Bazzana et al. (2022) framework. The model simulated 50-year trajectories of CSA adoption and multidimensional food security outcomes under five scenarios, using 100 Monte Carlo replications per scenario across 12 climate models.

Five main findings emerge. First, CSA adoption—especially WSA—significantly improves food security, with double adopters achieving near-complete food availability (0.991) by period 30, compared to 0.930 for non-adopters. Food security improvements operate through both direct (higher yields) and indirect (higher income enabling market food purchases) channels, with positive WSA externalities benefiting neighboring farms. Second, community social networks are critical drivers of WSA adoption: higher network participation (70%) generates better self-sufficiency and lower food instability, while lower participation (40%) leaves more households in food insecurity. However, network information can paradoxically reduce CP adoption when community skepticism about crop rotation prevails—calling for quality, not just coverage, of extension service information. Third, market integration is essential for translating CSA benefits into food security improvements: remote, market-isolated communities show 31.6 percentage points higher severe food insecurity severity in critical early periods, with persistent higher food instability throughout the simulation. Fourth, CSA provides significant but incomplete

protection against severe climate change (RCP 8.5): WSA-adopting farmers are clearly better off than non-adopters, but food instability remains persistently higher under worst-case scenarios, requiring complementary global climate mitigation. Fifth, distributional heterogeneity is substantial: bottom-quartile households benefit least from CSA adoption due to capital constraints, creating poverty trap dynamics requiring direct policy intervention.

5.2 Policy Recommendations

5.2.1 Strengthening Agricultural Extension Services and Farmer Networks

The simulation results demonstrate that community network participation is a key determinant of WSA adoption and food security. Pakistan's agricultural extension system—which suffered severe budget cuts following the 18th Constitutional Amendment devolving agricultural services to provinces—needs substantial reinvestment and reform. Policy makers should develop farmer field school programs leveraging community structures (water user associations, village committees) to expand information sharing about CSA benefits. Extension programs should focus not only on expanding network reach but on improving information quality, particularly regarding long-run returns to soil conservation investment. The model's finding that networks can reduce CP adoption when community information is skeptical of crop rotation argues for demonstration plots and peer learning experiences generating first-hand evidence of CP benefits, rather than information campaigns alone. Pakistan's provincial agriculture departments, supported by the National Agricultural Research System (NARS), should develop a CSA extension curriculum with particular emphasis on soil health management, crop rotation design, and water conservation—calibrated to the specific agro-ecological conditions of Punjab's diverse sub-regions.

5.2.2 Expanding Access to Agricultural Credit for CSA Investment

The distributional analysis consistently shows that financial constraints are the primary barrier preventing resource-limited smallholders from investing in WSA practices. Pakistan's agricultural credit programs—ZTBL, commercial bank agricultural lending, and microfinance institutions—reach only a small fraction of smallholder farmers, with formal credit access particularly limited in South Punjab. The government should expand concessional credit programs specifically linked to CSA technology adoption, with loan structures matched to the multi-year payback period of WSA investments. The simulation's robustness analysis showing that longer-lasting WSA practices (20 years vs. 5 years) generate substantially better food security outcomes argues for public co-investment in higher-quality, more durable soil conservation infrastructure alongside private adoption incentives. Direct input support and CSA technology subsidies should be considered for the poorest smallholder households unable to access even concessional credit.

5.2.3 Investing in Rural Market Infrastructure, Especially in South Punjab

The market access scenario provides compelling evidence that rural road and market infrastructure investments are a high-priority complement to CSA promotion, particularly in South Punjab. The stark food security cost of market isolation (31.6 percentage points higher severe insecurity in early periods) substantially exceeds the food security benefit of any single CSA technology investment. Pakistan's National Development Plan and provincial Annual Development Programs should prioritize all-weather rural road connectivity for food-insecure districts in South Punjab, recognizing that market integration

investments generate CSA-complementary benefits that multiply their direct economic returns. The CPEC-linked infrastructure investments in South Punjab represent a potentially transformative opportunity for market integration, and their food security co-benefits should be explicitly monitored and documented. Government investment in rural market infrastructure should be complemented by development of rural cold chain infrastructure to reduce post-harvest losses—currently estimated at 15-40% for perishable crops in Pakistan—which compound the food security losses from production shocks.

5.2.4 Integrating Social Protection with CSA Promotion

The heterogeneity analysis demonstrates that the bottom 20-25% of households by wealth and land access require targeted interventions beyond CSA promotion to achieve adequate food security. Pakistan's social protection system—including the Benazir Income Support Programme (BISP) and the Ehsaas initiative—should be explicitly integrated with agricultural development programs to provide a consumption floor enabling the poorest households to invest in CSA practices. The government should explore conditional cash transfer programs tied to CSA adoption, similar to successful models in Latin America, that simultaneously address current consumption needs and long-term agricultural productivity investment. Land tenure reform policies improving security of tenure for tenant farmers and sharecroppers—who currently have limited incentive to invest in CSA practices improving long-term soil fertility—deserve urgent attention, particularly in Punjab where sharecropping arrangements remain widespread.

5.2.5 Combining CSA Promotion with Global Climate Mitigation Advocacy

The severe climate scenario analysis delivers a clear message: CSA adoption is a necessary but insufficient response to worst-case climate change. The persistent increase in food instability under RCP 8.5 even with high CSA adoption rates indicates that Pakistan cannot adapt its way to food security under the most extreme climate scenarios. This finding strongly supports Pakistan's advocacy at international climate negotiations for ambitious global emissions reductions and its climate diplomacy strategy emphasizing climate justice for highly-vulnerable, low-emissions developing countries. Domestically, complementary investments in food price stabilization mechanisms—strategic wheat reserves, targeted wheat subsidies, and social protection programs—are needed to buffer the most vulnerable households against the heightened price volatility that worst-case climate scenarios generate.

5.3 Limitations and Future Research Directions

This study has several limitations. First, the model is calibrated to a representative Punjab village and may not fully capture Pakistan's agricultural diversity across Khyber Pakhtunkhwa, Balochistan, and Sindh. Future work should apply the ABM framework to these different contexts. Second, the model does not capture the role of feudal land tenure in some districts, the Islamic agricultural finance system, or the institutional capacity differences across provincial extension services. Third, the model abstracts from inter-household credit and insurance markets important for smallholder risk management. Fourth, future research should validate model predictions against observed trends as longer time-series data become available. Finally, extending the model to capture interactions between agricultural adaptation and the growing rural-urban migration trend in Pakistan would provide valuable insights for integrated rural development policy. Notwithstanding these limitations, this study makes an important methodological contribution by demonstrating the feasibility and policy value of applying ABM to CSA

dynamics in Pakistan's agricultural context, establishing a foundation for future extensions and applications.

References

- Ahmad, M., Iqbal, M. A., Chand, R., & Ishaq, M. (2015). Climate variability and its impacts on food production in Pakistan. *Pakistan Journal of Agricultural Sciences*, 52(4), 1075-1080.
- Ahmad, S., Abbas, G., Ahmed, M., Fatima, Z., Anjum, M. A., Rasul, G., & Hoogenboom, G. (2019). Climate warming and management impact on the change of phenology of the rice-wheat cropping system in Punjab, Pakistan. *Field Crops Research*, 230, 46-61.
- Agriculture Department, Government of Punjab. (2023). Punjab agriculture overview. Retrieved from <https://agripunjab.gov.pk/overview>
- Ali, A., Hussain, I., Rahut, D. B., & Erenstein, O. (2017). Coping with climate change in Pakistan: Farmer perceptions, knowledge and strategies. *Environmental Science and Policy*, 78, 132-141.
- An, L. (2012). Modeling human decisions in coupled human and natural systems: Review of agent-based models. *Ecological Modelling*, 229, 25-36.
- Bakker, C., Zaitchik, B. F., Siddiqui, S., Hobbs, B. F., Broaddus, E., Neff, R. A., & Parker, C. L. (2018). Shock, seasonality, and disaggregation: Modelling food security through the integration of agricultural, transportation, and economic systems. *Agricultural Systems*, 164, 165-184.
- Bazzana, D., Zaitchik, B., & Gilioli, G. (2020). Impact of water and energy infrastructure on local well-being: An agent-based analysis of the water-energy-food nexus. *Structural Change and Economic Dynamics*, 55, 165-176.
- Bazzana, D., Gilioli, G., Simane, B., & Zaitchik, B. (2021). Analyzing constraints in the water-energy-food nexus: The case of eucalyptus plantation in Ethiopia. *Ecological Economics*, 180, 106875. <https://doi.org/10.1016/j.ecolecon.2020.106875>
- Bazzana, D., Foltz, J., & Zhang, Y. (2022). Impact of climate smart agriculture on food security: An agent-based analysis. *Food Policy*, 111, 102304. <https://doi.org/10.1016/j.foodpol.2022.102304>
- Berger, T., Troost, C., Wossen, T., Latynskiy, E., Tesfaye, K., & Gbegbelegbe, S. (2017). Can smallholder farmers adapt to climate variability, and how effective are policy interventions? Agent-based simulation results for Ethiopia. *Agricultural Economics*, 48(6), 693-706.
- Bramouille, Y., & Kranton, R. (2016). Games played on networks. In Y. Bramouille, A. Galeotti, & B. W. Rogers (Eds.), *The Oxford handbook of the economics of networks*. Oxford University Press.
- Chandio, A. A., Jiang, Y., Rehman, A., & Rauf, A. (2020). Short and long-run impacts of climate change on agriculture: An empirical evidence from China. *International Journal of Climate Change Strategies and Management*, 12(2), 201-221.
- Conley, T. G., & Udry, C. R. (2010). Learning about a new technology: Pineapple in Ghana. *American Economic Review*, 100(1), 35-69.
- Conlisk, J. (1996). Why bounded rationality? *Journal of Economic Literature*, 34(2), 669-700.
- Delli Gatti, D., Desiderio, S., Gaffeo, E., Cirillo, P., & Gallegati, M. (2011). *Macroeconomics from the bottom-up*. Springer.

- Duflo, E., Kremer, M., & Robinson, J. (2011). Nudging farmers to use fertilizer: Theory and experimental evidence from Kenya. *American Economic Review*, 101(6), 2350-2390.
- FAO. (2013). *Climate-smart agriculture sourcebook*. Food and Agriculture Organization of the United Nations.
- FAO. (2021). *The state of food security and nutrition in the world 2021*. FAO, IFAD, UNICEF, WFP and WHO.
- FAO Pakistan. (2022). *Pakistan floods 2022: Post-disaster needs assessment for the agriculture sector*. FAO Country Office, Islamabad.
- Feder, G., Just, R. E., & Zilberman, D. (1985). Adoption of agricultural innovations in developing countries: A survey. *Economic Development and Cultural Change*, 33(2), 255-298.
- Foster, A. D., & Rosenzweig, M. R. (1995). Learning by doing and learning from others: Human capital and technical change in agriculture. *Journal of Political Economy*, 103(6), 1176-1209.
- Funk, C., Peterson, P., Landsfeld, M., Pedreros, D., Verdin, J., Shukla, S., & Michaelsen, J. (2015). The climate hazards infrared precipitation with stations—A new environmental record for monitoring extremes. *Scientific Data*, 2(1), 1-21. <https://doi.org/10.1038/sdata.2015.66>
- Government of Pakistan (GOP). (2022). *Pakistan floods 2022: Post-disaster needs assessment*. Planning Commission, Islamabad.
- Government of Pakistan (GOP). (2023). *Pakistan economic survey 2022-23*. Ministry of Finance, Islamabad.
- Groeneveld, J., Muller, B., Buchmann, C. M., Dressler, G., Guo, C., Hase, N., & Schwarz, N. (2017). Theoretical foundations of human decision-making in agent-based land use models. *Environmental Modelling & Software*, 87, 39-48.
- Gupta, R. K., Naresh, R. K., Hobbs, P. R., Jianguo, Z., & Ladha, J. K. (2010). Sustainability of post-green revolution agriculture: The rice-wheat cropping systems of the Indo-Gangetic Plains and China. In J. K. Ladha et al. (Eds.), *Improving the productivity and sustainability of rice-wheat systems* (pp. 1-25). ASA, CSSA, SSSA.
- Hussain, J., Khalid, M., Ahmad, I., & Noor, M. (2023). Assessing the impact of rising temperatures on wheat yield in Pakistan. *Pakistan Journal of Agricultural Sciences*, 60(1), 45-58.
- Immerzeel, W. W., Van Beek, L. P., & Bierkens, M. F. (2010). Climate change will affect the Asian water towers. *Science*, 328(5984), 1382-1385.
- Iqbal, M. A., Rizwan, M., Khan, M. A., Farooq, M., & Akhtar, M. N. (2022). Climate-smart agricultural practices and their impact on wheat yield and income in Punjab, Pakistan. *Environmental and Sustainability Indicators*, 14, 100178.
- Kamal, S. (2021). *Pakistan food security profile*. World Food Programme Pakistan Country Brief. WFP, Islamabad.
- Naseem, S., Ji, G., Kashif, U., & Takaichi, H. (2025). Climate variability, population growth, and globalization impacting food security in Pakistan. *Scientific Reports*, 15, 4289. <https://doi.org/10.1038/s41598-025-88916-2>
- National Disaster Management Authority (NDMA). (2022). *Pakistan 2022 floods: Situation reports*. Government of Pakistan, Islamabad.
- Pakistan Agricultural Research Council (PARC). (2021). *National report on soil degradation and land management*. PARC, Islamabad.
- Pakistan Bureau of Statistics (PBS). (2023). *Pakistan demographic survey 2021*. Government of Pakistan, Islamabad.

- Pakistan Economic Survey. (2023-24). Chapter 2: Agriculture. Ministry of Finance, Government of Pakistan, Islamabad.
- Pakistan Meteorological Department. (2022). Annual climate report for Pakistan 2021. Government of Pakistan, Islamabad.
- Pakistan Meteorological Department. (2023). Climate-related disaster report: 2023 heatwave. Government of Pakistan, Islamabad.
- Qureshi, A. S., Akhtar, M., Shah, S. A., & Iqbal, M. M. (2019). Climate-smart agriculture in Pakistan: Experiences and lessons. In A. Mirzabaev & J. von Braun (Eds.), *Sustainable land management: Methods, achievements and potentials* (pp. 285-298). Springer.
- Rajbhandari, R., Shrestha, A. B., Kulkarni, A., Patwardhan, S. K., & Bajracharya, S. R. (2015). Projected changes in climate over the Indus river basin using a high resolution regional climate model (RegCM). *Climate Dynamics*, 44(1), 339-357.
- Sardar, A., Ma, W., Jiang, Y., & Bhutto, Z. A. (2021). Does adoption of climate-smart agriculture (CSA) practices improve farmers' crop income? Assessing the determinants and its impacts in Punjab province, Pakistan. *Environment, Development and Sustainability*, 23(9), 13702-13730. <https://doi.org/10.1007/s10668-020-01049-6>
- SCOPE Pakistan. (2022). Rural landlessness in Pakistan: An assessment. Society for Conservation and Protection of the Environment, Islamabad.
- Taylor, K. E., Stouffer, R. J., & Meehl, G. A. (2012). An overview of CMIP5 and the experiment design. *Bulletin of the American Meteorological Society*, 93(4), 485-498.
- Tesfatsion, L., & Judd, K. E. (2006). *Handbook of computational economics II: Agent-based computational economics*. North-Holland.
- University of Agriculture Faisalabad. (2023). Impact assessment of 2023 heat stress on basmati rice yields in Punjab. Research Report, Department of Agronomy, UAF.
- Williams, T. G., Guikema, S. D., Brown, D. G., & Agrawal, A. (2020). Resilience and equity: Quantifying the distributional effects of resilience-enhancing strategies in a smallholder agricultural system. *Agricultural Systems*, 182, 102832.
- World Bank. (2013). *Turn down the heat: Climate extremes, regional impacts, and the case for resilience*. The World Bank.
- World Bank. (2021). *Pakistan rural financial access review*. The World Bank Group.
- World Food Programme (WFP). (2023). *Food security monitoring and climate risk in Pakistan*. WFP Country Brief, Islamabad.
- World Weather Attribution (WWA). (2022). *Climate change likely increased extreme monsoon rainfall, flooding highly vulnerable communities in Pakistan*. WWA Technical Report.
- Zhang, Y., You, L., Lee, D., & Block, P. (2020). Integrating climate prediction and regionalization into an agro-economic model to guide agricultural planning. *Climatic Change*, 158, 435-451.